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The effect of (strong) discrete absorption systems on the Lyman-α forest flux power spectrum

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ABSTRACT
We demonstrate that the Lyman-α forest flux power spectrum of "randomised" QSO absorption spectra is comparable in shape and amplitude to the flux power spectrum of the original observed spectra. In the randomised spectra a random shift in wavelength has been added to the observed absorption lines as identified and fitted with VPFIT. At 0.03 s/km $< k <$ 0.1 s/km the "3D" power spectrum of the randomised flux agrees with that of observed spectra within the errors. At larger scales it is still $\gtrsim 50\%$ of that of the observed spectra. At smaller scales the flux power spectrum is dominated by metal lines. Lines of increasing column density contribute to the "3D" flux power spectrum at increasingly larger scales. Lines with $13 < \log(N_{\rm HI}/\,{\rm cm}^{-2}) < 15$ dominate at the peak of the "3D" power spectrum while strong absorbers with $\log(N_{\rm HI}/\,{\rm cm}^{-2}) > 15$ dominate at large scales, $k < 0.03$ s/km. We further show that a fraction of up to 20% of the mean flux decrement is contributed by strong absorbers. Analysis of the flux power spectrum which use numerical simulations with too few strong absorption systems calibrated with the observed mean flux are likely to underestimate the inferred *rms* fluctuation amplitude and the slope of the initial DM matter power spectrum. In a combined analysis with other data which constrains the DM power spectrum on larger scales this can result in a spurious detection of a running spectral index.

Key words: Cosmology: intergalactic medium – large-scale structure of universe – quasars: absorption lines

1 INTRODUCTION

In the mid 1990s a paradigm shift occurred in the interpretation of the Lyman-α forest. Instead of being caused by small (kpc size) "Lyman-α clouds" it is now widely believed that most of the absorption arises from smooth fluctuations in the density of a photoionized warm intergalactic medium (see Rauch 1998 and Weinberg 1999 for reviews). Traditionally absorption spectra had been decomposed into Voigt profiles which have then been identified with individual discrete absorption systems. For these absorbers column density and Doppler parameter distribution and correlation function were determined (Rauch 1998). With the new paradigm the emphasis of the analysis has shifted to statistical measures more suitable for absorption arising from a continuous density field, most notably the flux decrement distribution and the flux power spectrum. While the clustering signal in the correlation function of discrete absorbers was very weak for all but the strongest absorption systems (Cristiani et al. 1995) the flux power spectrum indicated *rms* fluctuations of 10-30% on scales of a few Mpc decreasing as a power-law towards larger scales. This was generally interpreted as a detection of the clustering of the matter distribution. Due to non-linear and saturation effects the relation to the dark matter(DM) power spectrum is not straightforward even on large scales. Numerical simulations are therefore used to constrain amplitude and slope of the matter power spectrum. The constraints are broadly consistent with the so called concordance model of structure formation (Croft et al. 1999, McDonald et al. 2000, Croft et al. 2002, Kim et al. 2003 (K03), Viel et al. 2003). Recently a combined analysis of Lyman-α forest and WMAP data has been used to argue that a spectral index of the initial matter fluctuation spectrum < 1 and/or a running running spectral index is indicated by the data (Spergel et al. 2003, Verde et al. 2003). The errors are still large (Seljak, McDonald &

Makarov 2003) and the hope is that tighter constraints can be obtained from the SDSS sample of QSO absorption spectra (Mandelbaum et al. 2003) . However, the reason why the clustering signal in the correlation function of weak absorption systems is apparently so much weaker than that in the flux power spectrum has not been investigated in detail. Press, Rybicky & Schneider (1993) have demonstrated that the *rms* fluctuation of the flux distribution on scales of 25 Å due to randomly distributed absorption lines is comparable to the observed fluctuations. Zuo & Bond (1994) have shown that the flux correlation function of low-resolution absorption spectra can be reproduced by a superposition of randomly distributed absorption lines. It is thus astonishing that the flux power spectrum of a random distribution of absorption systems has not yet been investigated.

Here we have studied the flux power spectrum of a sample of 8 randomised high-resolution absorption spectra taken with the VLT-UVES spectrograph for which a complete decomposition into Voigt profiles due to hydrogen and metal lines absorption lines had been performed previously (Kim et al. 2001, Kim et al. 2002). In section 2 we describe the data. Section 3 compares the flux power spectrum of randomised and observed spectra. Section 4 investigates the effect of strong absorption systems. In Section 5 we discuss consequences for the inferred DM power spectrum and in Section 6 we give our conclusions.

2 THE DATA

The sample consists of 8 spectra taken with the Ultra-Violet Echelle Spectrograph (UVES) on VLT. The 8 spectra were taken from the ESO archive. The median redshift of the sample is $< z >= 2.43$ In Table 1 we list the Lyman-α redshift range, wavelength range and signal-to-noise ratio of the sample. The data reduction is described in Kim et al. (2001, 2002, 2003). Line lists for hydrogen and metal absorption have been compiled with the fitting routine VPFIT (Carswell et al.: http://www.ast.cam.ac.uk∼rfc/vpfit.html). For each of the 8 spectra we have produced randomised spectra where we have randomly shifted the hydrogen lines in wavelength. This procedure results in spectra with a column density distribution which is very similar to that of the observed spectra. Note, however, that there will be some incompleteness at the low column density end due to lines which have not been identified by the fitting procedure due to blending. We have also produced randomised spectra where we restricted the input list of hydrogen lines to certain column density ranges.

3 THE FLUX POWER SPECTRUM OF RANDOMISED SPECTRA

3.1 Calculating the flux power spectrum

The observed intensity is related to the emitted intensity as $I_{\rm obs} = I_{\rm em} e^{-\tau}$. The fluctuations in the observed intensity are thus a superposition of the fluctuations of the emitted intensity and those of the absorption optical depth. We use here continuum-fitted spectra and consider the quantity $F = I_{\rm obs}/I_{\rm em} = e^{-\tau}$ (F1 in the notation of Kim et al. 2003). Our procedure for calculating the flux power spectrum is described in detail in K03 and we give here just a short summary.

Table 1. QSO absorption spectra

QSO	$z_{\rm Ly\alpha}$	$\lambda_{\rm Ly\alpha}$(Å)	S/N
Q0055–269	2.93–3.61	4778–5603	30-75
Q0302–003	2.95–3.24	4807–5156	55-75
HE2347–4342	2.29–2.84	4002–4669	40-60
Q1101–264	1.65–2.11	3224–3780	30-70
HE1122–1648	1.88–2.37	3507–4098	35-65
HE1347–2457	2.05–2.57	3711–4352	50-70
HE2217–2818	1.88–2.38	3503–4107	35-60
J2233–606	1.74–2.22	3337–3912	30-50

The "3D" flux power spectrum is obtained via numerical differentiation of the 1D flux power spectrum,

$$P_{\rm F}^{\rm ``3D''}(k) = -\frac{2\pi}{k}\frac{d}{dk} P_{\rm F}^{\rm 1D}(k). \quad (1)$$

The dimensionless "3D" power spectrum is given by,

$$\Delta^2_{\rm F}(k) = \frac{1}{2\pi^2}\, k^3\, P_F^{\rm ``3D''}(k)\ . \quad (2)$$

Jackknife estimates are used to calculate the errors. In order to remind the reader that peculiar velocities and thermal broadening make the flux field anisotropic and that equation (2) does not give the true 3D power spectrum we denote it as "3D" power spectrum as in K03.

3.2 Flux power spectra of observed and randomised absorption spectra

In Fig. 1a we compare the 1D flux power of the sample of observed spectra to that of a sample of randomised spectra. For each observed spectrum we have produced 150 randomised versions. At wavenumbers 0.03 s/km $< k <$ 0.1 s/km the 1D flux power spectra are remarkably similar. At larger scales the flux power spectrum becomes close to constant as expected for a random distribution of discrete absorption features. This suggests that the shape of the absorption lines as identified by a Voigt profile fitting routine dominates the flux power spectrum over a wide range of scales. The discrepancy at $k > 0.1$ s/km is expected as the flux power spectrum of the observed absorption spectra is dominated by metal lines at these small scales (K03) which are not included in the randomised spectra. The contribution of large scale correlations in the density field is responsible for the difference at large scales but astonishingly these appear to be a relatively small contribution to the overall flux power spectrum. To investigate this in more detail we plot the corresponding "3D" flux power spectra in Fig 1b. As suspected from inspection of Fig. 1a at the peak the "3D" flux power spectra are identical to within the errors. At larger scales the variance of the

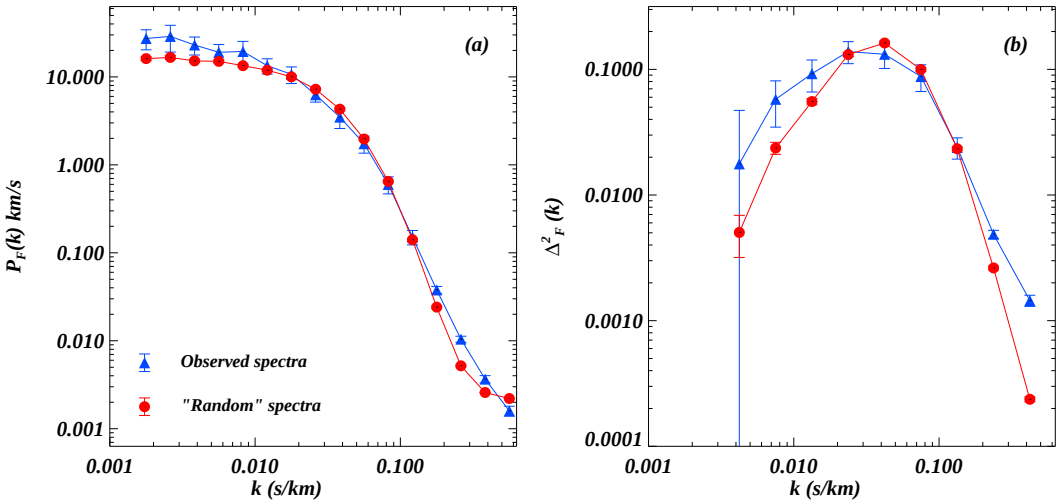

Figure 1. *Left:* The 1D flux power spectrum of a sample of observed and randomised spectra. *Right:* "3D" power spectrum

randomised spectra is still $\gtrsim 50$ % of that of the observed spectra. This may explain why Cristiani et al. (1995) only found a very weak signal for strong absorption systems when they investigated the clustering of absorption lines. It also explains why linear theory gives a bad approximation to the "3D" flux power spectrum, even at scales $k \sim 0.003-0.001$ s/km (Croft et al. 2002) and why numerical simulations are essential for inferring the DM power spectrum on these scales.

To address the question whether it is really the shape of the individual Voigt profiles which is responsible for the bulk of the flux power spectrum we have also calculated randomised spectra where we halved and doubled the Doppler parameter of the lines. The resulting "3D" power spectra are compared in Figure 2b. Broadening and narrowing of the lines leads to an approximately linear shift in wavenumber.

4 THE EFFECT OF STRONG DISCRETE ABSORPTION LINES

4.1 Strong absorption lines and the flux power spectrum

In Fig. 2a we have splitted the "3D" flux power spectrum into contributions from lines of different column density ranges. Lines of different column density ranges do not add exactly linearly but the relative contributions should nevertheless become apparent in this way. There is a clear trend with larger column density systems contributing at larger scales. The strongest contribution comes from absorption lines in the range $13.5 < \log(N_{\rm HI}/\,{\rm cm}^{-2}) < 14.5$. These are lines where the "curve of growth" which describes the relation between equivalent width and column density of absorption lines changes from the linear to the flat regime due to saturation. Such a behaviour can be understood if the different column density ranges contribute with their total equivalent width, $\mathcal{N}_{\rm lines} \times {\rm EW}$, to the "3D" power spectrum. The number of lines scales roughly as as $\mathcal{N}_{\rm lines} \propto N_{\rm HI}^{-0.5}$. The contribution to the total equivalent width has therefore a maximum for column densities at the transition of the curve of growth from linear to flat. Note that Press et al. (1993) had already demonstrated that the rms fluctuation of the flux can be explained with randomly distributed lines with a contribution $\propto EW^2$ to the 1D variance of the flux.

4.2 Strong absorption lines and the mean flux decrement

With increasing size of the data sets the mean flux decrement of absorption spectra has been determined reasonably well (Press et al. 1993, Rauch et al. 1997, Kim et al. 2002, Bernardi et al. 2003). It is nevertheless striking that the mean flux decrement varies considerably between different QSOs. The main reason for this is likely to be the large contribution of strong absorption systems. In Fig. 3a we have used the bottom four of the spectra listed in Table 1 to quantify the contribution of absorption lines in different column density ranges to the mean flux decrement by successively removing low column density lines. These four spectra were chosen because they are at similar redshifts and thus have comparable total mean flux decrement. Up to 20 % of the flux decrement is due to absorption systems with $\log(N_{\rm HI}/\,{\rm cm}^{-2}) > 15$. In Fig. 3b we show a similar plot for the *rms* fluctuations of the flux. About 15-40% of the flux fluctuations are contributed by absorption from strong lines. Poisson noise of the rare strong absorption systems can thus indeed explain the significant differences of the mean flux decrement between different lines-of-sight (Press et al. 1993). Unfortunately the sample is too small to test the evolution of the contribution of strong absorption lines with redshift.

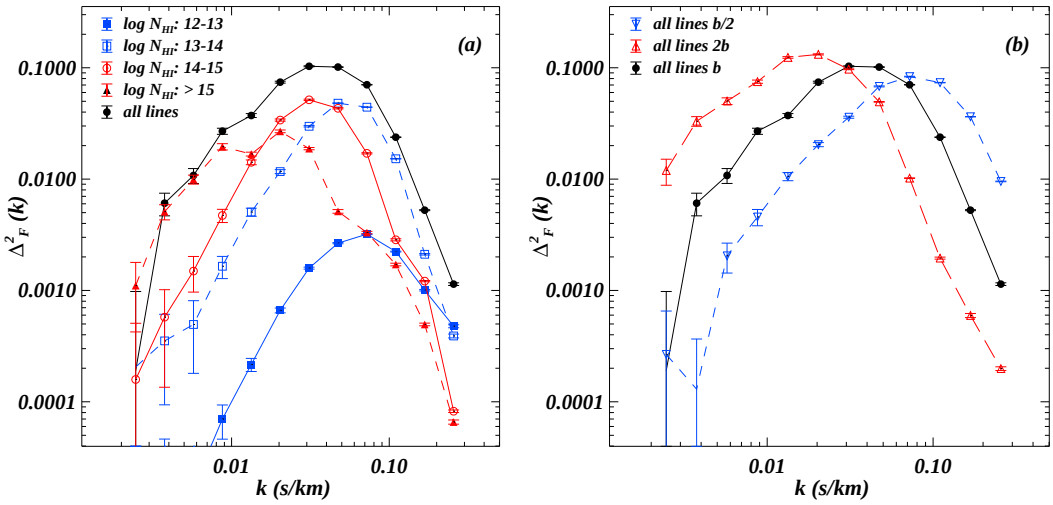

Figure 2. *Left:* Contribution of different column density ranges to the "3D" flux power spectrum of randomised absorption spectra. *Right:* The effect of halving and doubling the Doppler parameters.

5 STRONG ABSORPTION SYSTEMS AND ESTIMATES OF THE DARK MATTER POWER SPECTRUM

In the last section we had seen that strong absorption systems contribute significantly to both flux power spectrum and mean flux decrement. This will have profound implications for attempts to use numerical simulation together with QSO absorption spectra to infer amplitude and slope of the DM power spectrum with high accuracy. Numerical simulations of the Lyman-α forest often underpredict the number of strong absorption systems. Katz et al. (1996) *e.g.* found that in their hydro-simulations the number of Lyman limit systems falls short by a factor of ten compared to the observed number while Gardner et al. (2001) find a discrepancy of about a factor five. For the analysis of Lyman-α flux power spectra numerical simulation of the DM distribution which mimic the effect of gas pressure in an approximate way (so called Hydro-PM simulations) are widely used. These simulation have rather low resolution and the discrepancy already becomes large for lines with $\log(N_{\rm HI}/\,{\rm cm}^{-2}) > 14$ (Gnedin 1998).

The lack of strong absorption systems will affect the inferred matter power spectrum in two ways. If large column densities absorption systems contribute significantly to the observed flux power spectrum on large scales by their shape their absence has to be compensated by extra power due to density correlations on these scales. This will require a shallower slope of the DM power spectrum. Without detailed numerical simulations it is difficult to estimate how large this bias will be but considering the large contribution of strong absorption lines and the weak dependence of the slope of the flux power spectrum on the slope of the DM spectrum (Croft et al. 2002) it is unlikely to be smaller than the current errors of the slope and amplitude (McDonald et al. 2002, Croft et al. 2002). This should thus be a serious concern for upcoming determinations of the DM power spectrum with larger samples of spectra which aim at higher accuracy.

The second more subtle bias is due to the effect of strong absorption systems on the mean flux decrement. As discussed *e.g.* by Croft et al. (1998) the amplitude of Lyman-α flux power spectrum depends not only the amplitude of the matter power spectrum but there is also a strong dependence on the mean flux decrement. The amplitude of the flux power spectrum increases with increasing mean flux decrement.

Analyses of observed flux power spectra with numerical simulations therefore normally set the mean flux decrement in the artificial spectra produced from numerical simulations to that of observed spectra. This is a reasonable thing to do if the numerical simulations are a fair representation of the absorbers responsible for the flux decrement in observed spectra. The failure of the simulation to produce enough strong absorption systems shows, however, that this is not the case. In the case of the hydro-simulations this may be related to the fact that the ionization rate required to match the observed mean flux decrement with favoured values of the baryon density and temperature falls short of that estimated from QSO surveys and high redshift galaxies by a factor 2-4 (Rauch et al. 1997; Haehnelt et al. 2001). A population of strong absorption systems may thus be genuinely missing in numerical simulations. In the case of the hydro-PM simulations the insufficient spatial resolution is the obvious reason for the much more severe lack of strong absorption systems.

Calibration of numerical simulations which under-reproduce observed strong absorption systems using the observed mean flux decrement is thus clearly not the right thing to do. If it is nevertheless done the amplitude of the matter power spectrum inferred from the Lyman-α flux power spectrum will be systematically biased low. The simulated spectra reproduce then the observed flux

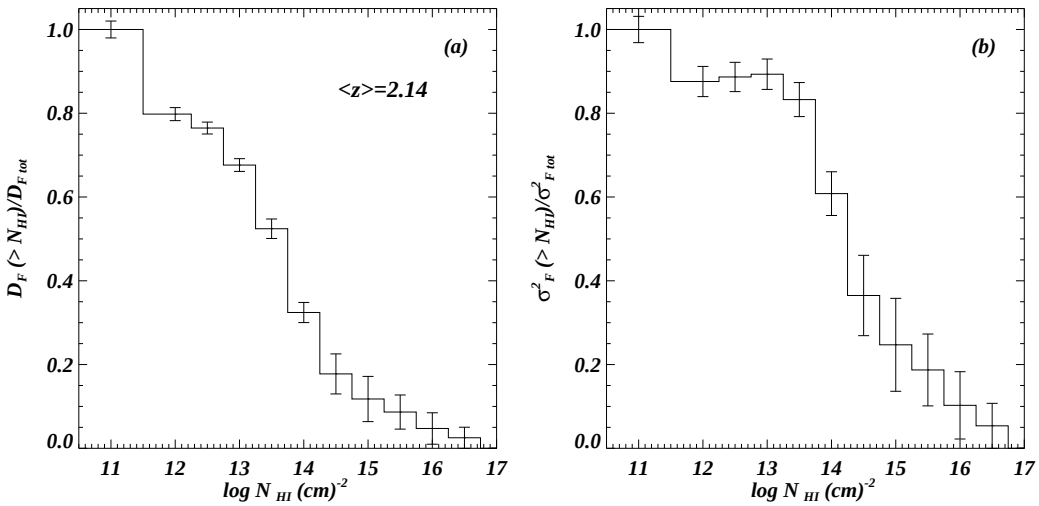

Figure 3. *Left:* Cumulative distribution of the contribution of different column density ranges to the mean flux decrement of four observed spectra. *Right:* Same for the *rms* amplitude of the flux.

fluctuations with a larger flux decrement and a smaller matter fluctuation amplitude. This effect is not small. Seljak, McDonald & Makarov (2003) found that a 20 % reduction of the effective optical depth used to calibrate the simulated spectra leads to a factor 2 increase of the inferred DM fluctuation amplitude. Note that if the inferred DM fluctuation amplitude at small scales is biased low a combined analysis with other data on larger scales (CMB, galaxy surveys) will lead to an underestimate of the spectral index. Alternatively, a spurious running of the spectral index may be inferred.

6 CONCLUSIONS

We used a sample of high-resolution, high signal-to-noise QSO absorption spectra taken with the ESO-UVES spectrograph for which line lists of hydrogen and metal absorption systems are available to investigate the effect of discrete absorption systems on Lyman-α flux power spectra. The basic shape and amplitude of the Lyman-α flux power spectrum is well reproduced by a random superposition of Voigt profiles. Only at wavelengths larger than $k < 0.03$ s/km a weak clustering signal appears to be detected. However, even there the contribution from strong absorption systems is still $\gtrsim 50\%$. The contribution of strong absorption systems to the mean flux decrement is also large, up to 20% for absorption systems with $\log(N_{\rm HI}/\,{\rm cm}^{-2}) > 15$. Simulated absorption spectra often underreproduce the number of strong absorption systems. The use of such simulations calibrated to the observed mean flux for an analysis of Lyman-α forest flux power spectrum is likely to lead to an underestimate of the amplitude and initial slope of the inferred DM power spectrum.

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